The Impact of Omega Dropwindsonde Observations on Barotropic Hurricane Track Forecasts

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ABSTRACT

A scarcity of observations in the hurricane environment is one factor believed to be limiting the improvement in hurricane track forecast accuracy. Since 1982, the Hurricane Research Division (HRD) of the NOAA Atlantic Oceanographic and Meteorological Laboratory has conducted 14 experiments to determine the wind and thermodynamic fields within about 1000 km of tropical cyclones in the Atlantic basin. During these synoptic-flow experiments, Omega dropwindsondes (ODWs) are released from the two NOAA WP-3D research aircraft over a 9–10-h period in the hurricane environment. The ODWs measure pressure, temperature, humidity, and wind as they descend from flight level (about 400 mb) to the surface. These data are then transmitted in real time to the National Hurricane Center (NHC) and the National Meteorological Center (NMC).

Recently, a barotropic, nested, spectral hurricane track forecasting model, VICBAR, has been developed at HRD and tested quasi-operationally during the 1989 and 1990 hurricane seasons. Forecasts from this model have compared favorably with other models run at NHC and NMC. In this study, the VICBAR model is used to evaluate the impact of ODW data on track forecast error for the 14 HRD synoptic-flow experiments.

The ODW data produced highly consistent reductions in track forecast errors in this sample of cases. Forecast improvements due to single-level midtropospheric (aircraft) data were significantly smaller than those due to the ODWs. At the important verification times of 24–36 h (prior to landfall), when the decision to issue a hurricane warning is being made, the ODWs reduced the model mean forecast error by 12%–16%. These improvements, statistically significant at the 99% level, are comparable to the total improvement in normalized NHC official 24-h forecast error occurring over the past 20–25 years.

1. Introduction

There is evidence that an important factor limiting the improvement in hurricane track forecast accuracy is the scarcity of observations typically available in the storm environment (Neumann 1981, 1985). In recent years, the Hurricane Research Division (HRD) of the NOAA Atlantic Oceanographic and Meteorological Laboratory has made efforts to increase the number of such observations. Since 1982, HRD has conducted experiments to determine the wind and thermodynamic fields within about 1000 km of tropical cyclones in the Atlantic basin (Burpee et al. 1984). During these synoptic-flow experiments, Omega dropwindsondes (ODWs) are released from one or two of the NOAA Aircraft Operations Center (AOC) WP-3D research aircraft over a 9–10-h period in the hurricane environment. The ODWs measure pressure, temperature, humidity, and wind as they descend from flight level (400–500 mb) to the surface. These data are then transmitted in real time to the National Hurricane Center (NHC), where the data are plotted and made available to the hurricane forecasters, and to the National Meteorological Center (NMC), where the ODW data become part of the operational database. Since 1982, 14 synoptic-flow experiments in Atlantic tropical cyclones have been conducted.

Burpee et al. (1984) investigated the impact of the ODW data for the two experiments in Hurricane Debby, using NMC's operational analysis algorithms and the MFM (moveable fine-mesh model) (Hovermale and Livezey 1977). The results were inconclusive with regard to the impact on operational track forecasts, but they did indicate that NMC's objective analysis procedures were not taking full advantage of the ODW observations. Since then, there have been no published studies of the impact of these data on hurricane track forecasts.

The relatively modest impact of the ODW data on NMC analyses prompted the development of an objective analysis system at HRD (Lord and Franklin 1987). This analysis is based on Ooyama's (1987) spectral application of finite-element representation (SAFER) cubic-spline framework and has been used in several diagnostic studies of hurricane structure (e.g., Franklin 1990; Powell et al. 1991). An important enhancement to the original analysis software has been the multiple nesting of submeshes (Lord 1989, personal communication). Each submesh employs a succes-

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sively finer filtering of the available observations, with the analyzed fields continuous to the second derivative across each mesh interface.

Being developed in parallel was VICBAR, a barotropic, nested, spectral hurricane track forecast model (DeMaria 1989). This model, initialized using HRD's objective analyses, has been run in near real time at HRD during the 1989 and 1990 hurricane seasons, with the forecasts being made available to NHC. The performance of the VICBAR model during these two seasons (Aberson and DeMaria 1991) compares favorably with other NHC and NMC objective guidance. In this study, the VICBAR model is used to assess the impact of ODW data from the synoptic-flow experiments on hurricane track forecast errors.

2. The VICBAR analysis and forecasting system

A more complete description of the VICBAR model is given by DeMaria (1989), with a brief summary of the model and associated algorithms being presented here.

The VICBAR analysis and forecasting system consists of a multilevel analysis and a barotropic prediction model. Horizontal wind components and geopotential heights (actually, deviations from standard altitude, D values) are first analyzed at 850, 700, 500, 400, and 200 mb over a horizontal domain that covers a 40° × 40° latitude–longitude region centered on the storm. The objective algorithm of Lord and Franklin (1987) is used to produce these analyses of the storm environment, using a filter cutoff wavelength of 4° latitude. Each analysis accepts data over a broad pressure window: for example, all data falling between 400 and 600 mb are used in constructing the 500-mb fields. NMC gridded forecast fields from the aviation model are included as low-weighted background "observations" in the production of these analyses.

The initial condition for VICBAR is obtained by combining NMC aviation fields over the VICBAR model domain (27.5°S–67.5°N, 140°W–10°E) with the 40° × 40° storm environment analyses, vertically (mass-weighted) averaging to produce a 200–850-mb layer mean, and then adding a bogus vortex. The bogus vortex is calculated on a cylindrical grid that extends out to 600 km from the storm center, with radial and azimuthal spacings of 25 km and 22.5°, respectively. Bogus winds on this grid are determined by adding the operational current storm motion vector to an axisymmetric vortex, determined from operational NHC estimates of storm strength and size. The nested version of HRDs objective analysis is then used to generate an analysis of layer-mean winds and heights from this combined dataset, to initialize the forecast model. In the construction of the layer-mean analysis, winds from the NMC aviation run are not used within 12° latitude of the storm center, and winds from the storm environment analyses are not used within 3° of the center.

The VICBAR model uses the shallow-water equations with a mean fluid depth of 750 m on a Mercator projection. Variables in the prediction model are also represented by cubic splines, on four nested domains. Resolution on the innermost mesh is 50 km, and increases by a factor of 2 across each interface. The three interior meshes are centered on the storm and cover areas of 600, 1800, and 4800 km square, respectively. The multiply nested layer-mean initial wind and height analyses provide the model with winds for all four meshes and heights for the outer model mesh. The heights on the inner three meshes are obtained from the nonlinear balance equation using the outer mesh heights as boundary conditions. The use of the balance equation results in a dynamically consistent initial condition in the vortex region, even though no bogus heights are included in the analysis. The inner three meshes of the prediction model move to remain centered on the storm, with the forecast track being determined from the location of the maximum relative vorticity on the innermost mesh.

To improve the prediction of the large-scale flow away from the storm region, time-dependent boundary conditions are applied. For this purpose, nudging terms are added to the prediction equations to force the solution to the baroclinic NMC aviation model solution. The magnitude of these nudging terms increases with radius from the storm center; within a 1500-km radius of the storm center, the prediction is entirely barotropic, between the 1500- and 2500-km radii the prediction is a distance-weighted average of the barotropic and aviation forecasts, and for radii greater than 2500 km the prediction is entirely baroclinic.

The VICBAR model has been tested in near real time during the 1989 and 1990 hurricane seasons (Aberson and DeMaria 1991) and has produced skillful track forecasts relative to a climatology and persistence model (CLIPER). In the current study, the impact of the ODW observations on VICBAR track forecasts is tested. Many of the ODW observations are transmitted in real time and therefore have influenced the NMC analyses. During the 1990 season, however, the background and boundary condition fields used by VICBAR were taken from a 12-h-old NMC aviation model run. (The aviation forecasts were appropriately lagged so that, for example, the background field for VICBAR would be taken from the aviation forecast verifying at t = 12 h.) This configuration, which has been used in this study, prevents any direct influence of operationally transmitted ODW data on the results. Because several of the synoptic-flow experiments were conducted on successive days (24 h apart), there may be some residual "information" from ODWs transmitted 24 h earlier. It is not practical to recreate NMC's data assimilation cycle omitting the ODWs; however, any presence of residual information carried forward by data assimilation procedures is likely to result in an underestimate of the actual impact of the ODWs on the model tracks.

TABLE 1. Synoptic-flow experiments conducted in Atlantic tropical cyclones. The time given is the nominal (central) time of the experiment. Also given is the (operational) location and status [hurricane (H) or tropical storm (TS)] of the cyclone at the nominal time of the experiment.

Storm	Date	Time (UTC)	H/TS	Latitude (°N)	Longitude (°W)
Debby	15 September 1982	0000	H	25.6	70.9
Debby	16 September 1982	0000	H	30.8	67.2
Josephine	10 October 1984	0000	TS	26.9	72.9
Josephine	11 October 1984	0000	H	28.5	72.3
Josephine	12 October 1984	0000	H	31.4	71.6
Gloria	25 September 1985	0000	H	24.0	69.8
Emily	24 September 1987	0000	TS	22.2	72.7
Emily	25 September 1987	0000	TS	27.9	70.4
Floyd	11 October 1987	0000	TS	17.7	83.8
Floyd	12 October 1987	0000	TS	21.9	84.3
Florence	9 September 1988	0000	TS	24.2	89.2
Hugo	20 September 1989	0000	H	23.4	69.2
Hugo	21 September 1989	0000	H	27.2	73.4
Jerry	14 October 1989	1200	TS	24.6	93.0
Mean storm position:				25.5	75.8

3. Data and sample of cases

Since 1982, HRD has conducted 14 synoptic-flow experiments on Atlantic tropical cyclones. The 14 cases (Table 1) were evenly split between hurricanes and tropical storms and represent 8 different tropical cyclones. Six of the eight storms required the issuance of hurricane warnings by NHC and later made landfall or passed over populated islands. Here 10 of the 14 cases were located in the western Atlantic in the area bounded roughly by Miami, San Juan, and Bermuda. The sample also includes two Caribbean cases and two Gulf of Mexico cases. All of the storms were within 1200 km of the United States coastline at the time of the experiment.

Because the sample of cases dates back to 1982, the NMC operational datasets for all of the cases are not readily available. A database of observations, examples of which are shown in Fig. 1, was reconstructed for each case. The following types of data were included:

(i) *Rawinsondes.* Soundings were obtained from the National Climatic Data Center in Asheville, North Carolina, for the 1982–88 cases. Data for the 1989 cases were obtained from the Domestic Data Plus circuit (part of the commercially available National Weather Service family of services). Mandatory- and significant-level wind and height data were filtered with a 100-mb low-pass linear filter and sampled at 50-mb resolution.

(ii) *Reconnaissance.* This includes U.S. Air Force vortex messages, supplementary vortex messages, and high-density (MINOB) and low-density (RECCO) flight-level observations.

(iii) *Cloud-motion vectors.* These were obtained from University of Wisconsin Cooperative Institute for Meteorological Satellite Studies (CIMSS) archives and/or from NMC operational files. NMC's operational

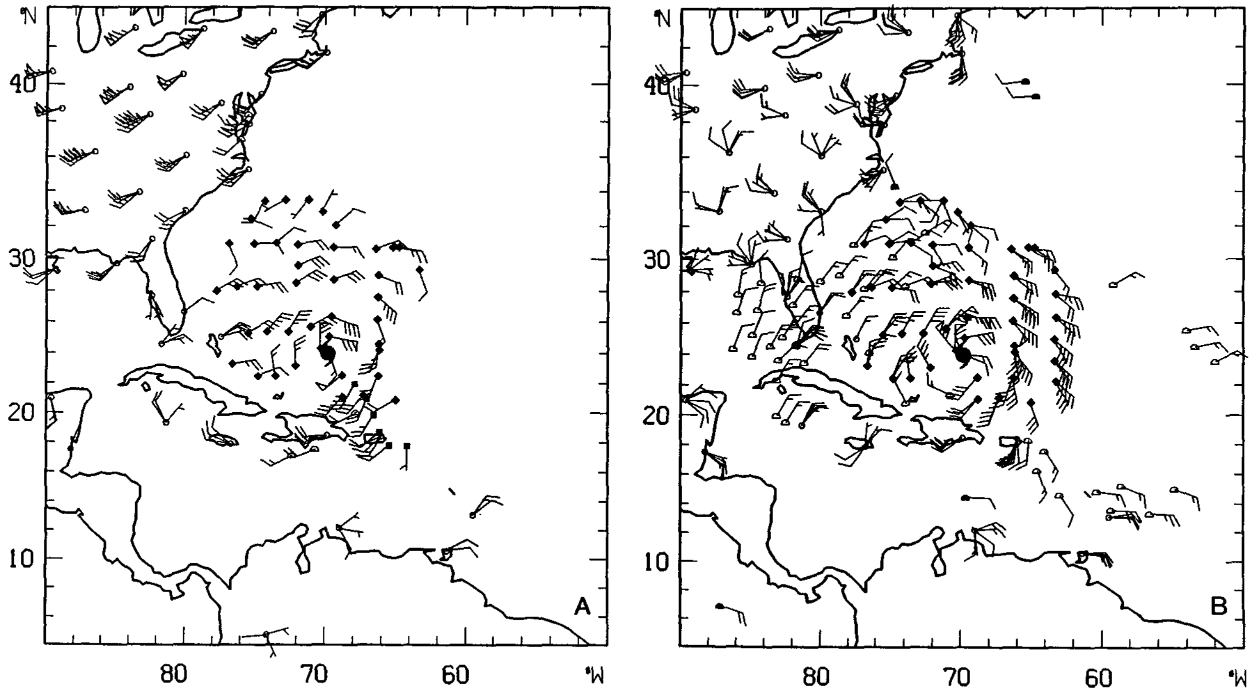

FIG. 1. Data coverage at (a) 500 and (b) 850 mb during the synoptic-flow experiment in Hurricane Gloria. Data types shown are ODWs (♦), rawinsondes (○), air force reconnaissance (■), NMC (◓), and Wisconsin (◠) cloud-track winds. Multiple rawinsonde observations are due to the depth of the pressure windows for data acceptance.

cloud-motion winds were obtained for each case. Additional high-density cloud-drift winds, generated in a pseudo-operational mode, were provided by CIMSS for the Debby, Gloria, Emily, Hugo, and Jerry cases.

(iv) *NOAA P-3 data.* Flight-level wind data were collected during the synoptic-flow experiments and processed by AOC after the flights. The observations used here, generally between 400 and 500 mb, are 1-min averages of the processed data taken every 5 min. Similar high-resolution observations are currently available operationally at NHC.

(v) *ODW data.* The impact of the ODWs has been assessed here using both operational and postprocessed ODW datasets, to provide upper- and lower-bound estimates of the value of the ODWs. The operational dataset consists of mandatory level winds and heights received at NHC during the experiments. These data received subjective quality control by HRD scientists prior to transmission from the aircraft. After each hurricane season, raw ODW data recorded on the P-3's are postprocessed. This processing, described by Franklin (1987), involves considerable subjective quality control, recalculation of the winds using edited Omega signals, and inclusion or recovery of some data not transmitted in real time. For this study, the postprocessed ODW data were additionally smoothed using a 100-mb low-pass linear filter and sampled every 50 mb.

A new workstation installed on the P-3 aircraft (Griffin et al. 1991) has greatly increased the quality and quantity of the operational ODW data that are transmitted in real time. Airborne processing now includes checks of each ODW's thermodynamic diagram, objective and subjective editing algorithms, hydrostatic checks, and filtering of the wind and thermodynamic sounding. Mandatory- and significant-level information are now transmitted back to NHC and NMC. Many of these procedures are similar to those used in the postseason processing. It is expected that the quality of future operational ODW datasets will be far superior to previous data and will approach the quality of the postprocessed data. For this reason the focus below will be on the impact of the postprocessed data.

4. Testing statistical significance

The test used for statistical significance is the paired t test (e.g., Larsen and Marx 1981). For each of N forecasts, the difference between (for example) the ODW forecast error and a control (no ODW) forecast error is calculated. This difference is simply the improvement due to adding ODWs to the control dataset. The null hypothesis is that the mean forecast improvement (MFI) is not significantly different from (better than) zero. Once an adjustment is made for the serial correlation between the forecast cases, the familiar t statistic and one-sided distribution are used to determine the level of significance.

Several of the synoptic-flow experiments are separated by 24 h. The results of Neumann et al. (1977) suggest that independence may not be fully attained with separations less than 30 h. An effective sample size N^* is estimated for each verification time using this 30-h criterion. If the time interval between two forecasts (Δt) is less than 30 h, the second forecast is counted as a fractional case ($\Delta t/30$). A forecast is counted fully if no other forecast precedes it by less than 30 h. Following Laurmann and Gates (1977), the effective sample size N^* is then used in place of N in the calculation of the t statistic and the degrees of freedom.

5. Results

a. Impact of ODW and P-3 data

VICBAR forecasts were run for the 14 cases of Table 1, using only the control database, consisting of rawinsonde, air force reconnaissance, NMC and Wisconsin cloud-motion vectors, and the NMC background field. This control database contains all of the data types typically available operationally for the VICBAR model. The Wisconsin winds, although not currently available to VICBAR in real time, were included in the control database in anticipation of their future availability. Because the background field is an NMC forecast using 12-h-old data, the control does not directly contain any ODW information transmitted operationally.

Additional sets of forecasts were run, in which data from the synoptic-flow experiments were added to the control data. In separate forecast sets, the postprocessed ODW, operational ODW, and P-3 data were added, and the forecasts were compared with the control forecasts. The mean forecast errors (relative to the control) for these experiments are shown in Fig. 2.

Figure 2 shows that adding the postprocessed ODWs to the control database reduced the mean forecast error (MFE) by more than 10% out through 36 h, with a positive impact observed out to 60 h. Results for 72 h are not shown because only 4 out of the 14 forecasts verified at this time. Out to 36 h, the operational ODWs were nearly as effective as the postprocessed ODWs at lowering forecast errors. Table 2 summarizes the impact of the postprocessed ODW data on the VICBAR model forecasts. The reduction of track error due to the ODW data is very consistent; the frequency of improved forecasts was >85% out to 48 h. At 36 h, the ODWs provided some improvement for every 36-h forecast. The mean forecast improvements (MFI) due to the ODWs were statistically significant at the 99% level at 12, 24, 36, and 48 h.

The P-3 data also produced reductions in MFE (Fig. 2), but these were only one-half to one-third as large as the ODWs'. Table 3 summarizes the impact of flight-level data from the P-3 aircraft. Reductions in forecast error were also less consistent than those due

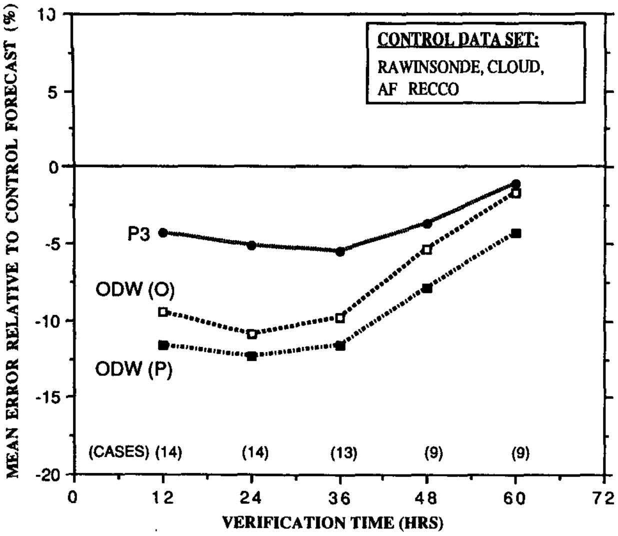

FIG. 2. Impact on mean VICBAR forecast errors of adding postprocessed ODW, operational ODW, and NOAA P-3 data to a control dataset. The control dataset contains rawinsonde, air force reconnaissance, and cloud-motion data. Errors are shown relative to the mean forecast error of the control.

to the ODWs; P-3 data improved forecasts roughly two times out of three, whereas the ODWs improved forecasts roughly nine times in ten. None of the P-3 MFIs were significant at the 99% level. The direct impact of adding ODWs to a dataset that *already* contains the P-3 data was also investigated (Table 4). These results demonstrate that the ODWs provide consistent additional benefit to the 12–48-h forecasts beyond what the aircraft provides.

Adding ODWs to the control database tended not to make dramatic or extreme changes to either the initial deep-layer-mean (DLM) analyses or to the forecast tracks; rather, the tendency was for the ODWs to nudge the forecast toward the best track. Figure 3 documents the impact on the DLM flow for three of the cases. ODW impact vanishes near the storm center due to the imposition of the bogus vortex. Outside the bogus region, only modest (<3 m s^{-1}) modifications to the DLM flow were typically effected by the ODWs, as illustrated for the Jerry and Gloria experiments (Figs. 3a,b). In both of these cases, the ODWs indicated stronger easterlies ahead of the storm than the NMC background analyses. A stronger back-to-front flow for Gloria (which was moving northwestward) was also resolved. The most dramatic changes to the DLM flow occurred in the Debby case on 16 September 1982. Here the ODWs were instrumental in resolving a cutoff low (Fig. 3c) that influenced Debby's subsequent 36-h track (Burpee et al. 1984). Figure 4 shows the VICBAR forecast tracks (with and without ODWs) for these three cases. The Jerry and Gloria forecasts were shifted to the west as a result of the stronger easterlies measured by the ODWs. Gloria's forecast motion was increased as well. The Debby forecast track turned more sharply to the left at 12 h, in response to the ODWs' better resolution of the cutoff low. In each case

TABLE 2. Comparative verification for forecasts using postprocessed ODW data versus forecasts not using the ODW data, for verification times (VT) of 12–60 h. Both sets of forecasts used rawinsonde, air force reconnaissance, and cloud motion data. The number of cases is *N*; the effective number of independent cases is *N**. MFE is the mean error for forecasts using the ODW data. Also shown are the mean, standard deviation (std dev), and frequency (freq) of the improvements due to adding the ODW data. SIG identifies whether the mean improvement is statistically different from zero at the 95% (*) or 99% (**) levels.

				Forecast improvements				
VT (h)	*N*	*N**	MFE (km)	Mean (%)	Mean (km)	std dev (km)	freq (%)	SIG
12	14	12.8	78	11.6	10	12	86	**
24	14	12.8	173	12.3	24	21	86	**
36	13	11.8	313	11.6	41	19	100	**
48	9	8.4	449	7.9	39	25	89	**
60	9	8.4	641	4.3	29	50	67	

TABLE 3. Comparative verification for forecasts using NOAA P-3 data versus forecasts not using the P-3 data. Both sets of forecasts used rawinsonde, air force reconnaissance, and cloud-motion data. MFE is the mean error for forecasts using the P-3 data. Also shown are the mean, standard deviation (std dev), and frequency (freq) of the improvements due to adding the P-3 data. Other quantities as defined in Table 2.

				Forecast improvements				
VT (h)	*N*	*N**	MFE (km)	Mean (%)	Mean (km)	std dev (km)	freq (%)	SIG
12	14	12.8	84	4.4	4	9	57	
24	14	12.8	188	5.1	10	20	71	*
36	13	11.8	335	5.5	19	30	77	*
48	9	8.4	470	3.7	18	41	67	
60	9	8.4	663	1.0	7	49	56	

TABLE 4. Comparative verification for forecasts using postprocessed ODW data versus forecasts not using the ODW data. Both sets of forecasts used NOAA P-3, rawinsonde, air force reconnaissance, and cloud-motion data. MFE is the mean error for forecasts using the ODWs. Also shown are the mean, standard deviation (std dev), and frequency (freq) of the improvements due to adding the ODWs. Other quantities as defined in Table 2.

				Forecast improvements				
VT (h)	*N*	*N**	MFE (km)	Mean (%)	Mean (km)	std dev (km)	freq (%)	SIG
12	14	12.8	78	7.0	6	10	79	*
24	14	12.8	175	6.5	12	19	71	*
36	13	11.8	315	6.0	20	19	92	**
48	9	8.4	449	4.4	21	24	78	*
60	9	8.4	643	3.0	20	47	67	

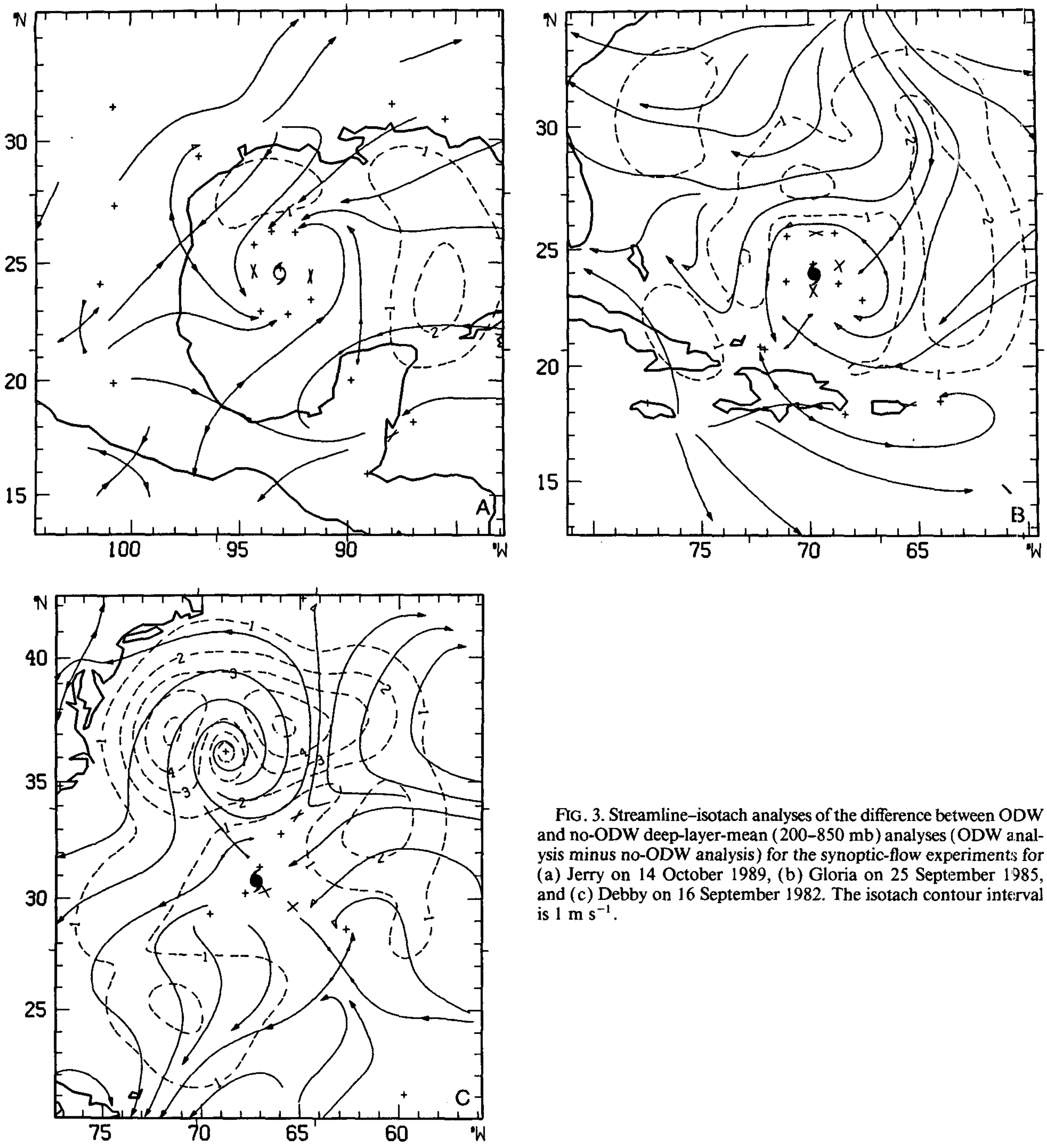

FIG. 3. Streamline–isotach analyses of the difference between ODW and no-ODW deep-layer-mean (200–850 mb) analyses (ODW analysis minus no-ODW analysis) for the synoptic-flow experiments for (a) Jerry on 14 October 1989, (b) Gloria on 25 September 1985, and (c) Debby on 16 September 1982. The isotach contour interval is 1 m s^{-1}.

the no-ODW forecast was improved upon, but the basic shape of the forecast was unchanged.

It is possible for the ODWs to reduce the MFEs even further. The objective analysis software allows for the assignments of weights to each data type (Lord and Franklin 1987); real observations (including the ODWs) are generally assigned a weight of 1.0, while the background field data from NMC analyses are assigned a lower weight. A series of tests was performed to determine the optimal background field weight for the *control dataset* (the no-ODW forecasts). Forecast errors for the control were not very sensitive to the choice of background field weight, but a value of 0.05 gave the lowest MFE. This weight was then used in all of the previously described experiments to assess the impact of the ODWs.

When ODWs are available in the storm environment, however, it may be advantageous to lower the

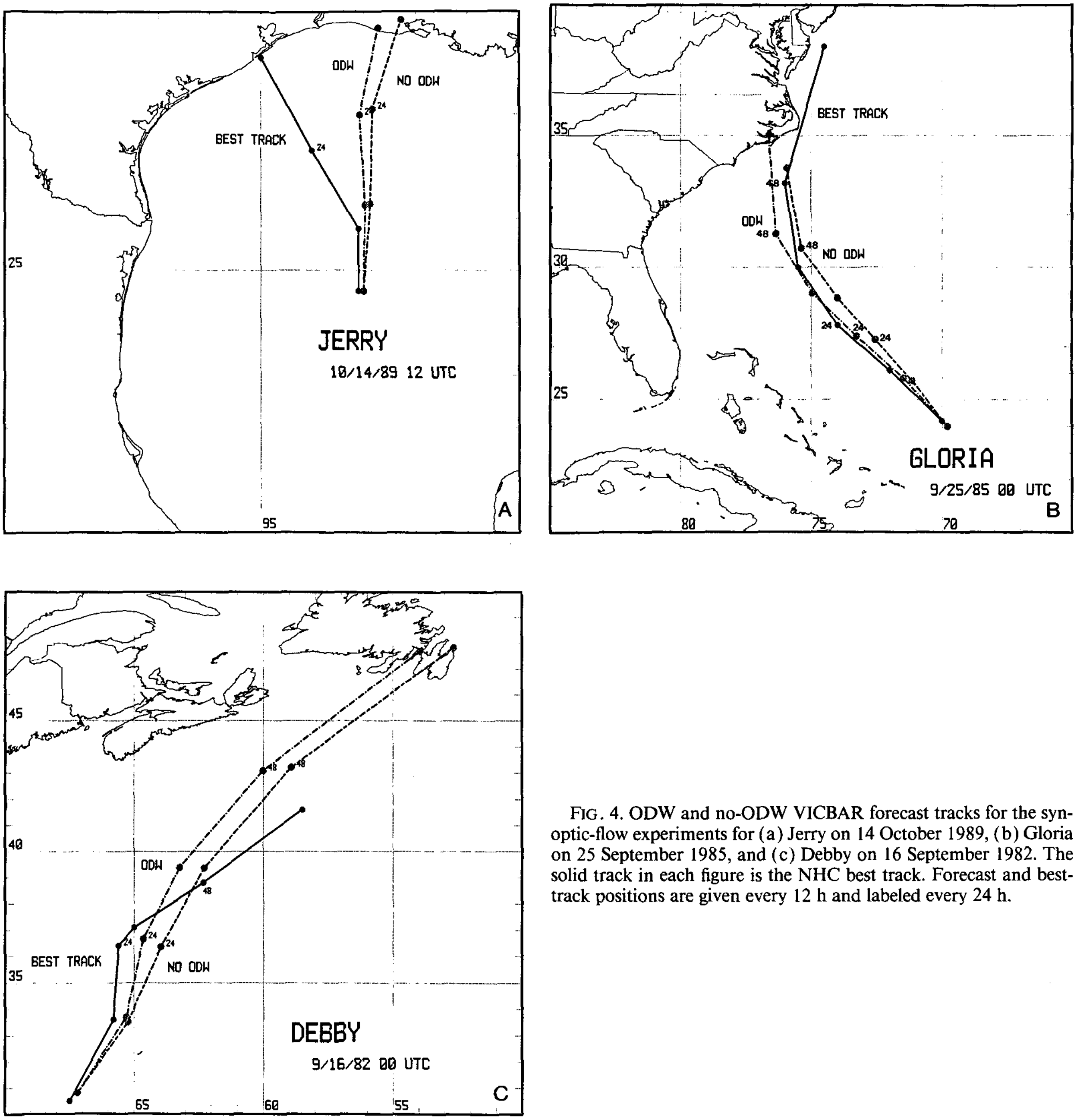

FIG. 4. ODW and no-ODW VICBAR forecast tracks for the synoptic-flow experiments for (a) Jerry on 14 October 1989, (b) Gloria on 25 September 1985, and (c) Debby on 16 September 1982. The solid track in each figure is the NHC best track. Forecast and best-track positions are given every 12 h and labeled every 24 h.

weight of the background field somewhat, to allow the ODWs greater influence on the model's initial analysis. Figure 5 shows the reduction of MFE due to the ODWs for several different background field weights. When the background weight is reduced from 0.05 to 0.01, 24–36-h ODW MFEs are reduced another 3%–4% relative to the control forecast. Continued reductions in background weight begin to give erratic results: ultralow weights (0.001) produce slightly greater reductions in MFE; however, forecast consistency (and statistical significance) begins to suffer at these values. This may be due to degradation of the analyses just beyond the edges of ODW coverage or to an increased sensitivity of the analyses to individual observations (of any type) that may not be representative. For this sample of cases, a background weight of 0.01 provides the best balance of consistency and reduced error, with the ODWs producing 24–36-h reductions in MFE of 15%–16%.

b. *Areal variability of impact*

The ODW datasets offer a rare, if not unique, opportunity to examine the sensitivity of hurricane track forecasts to various distributions of data in the storm

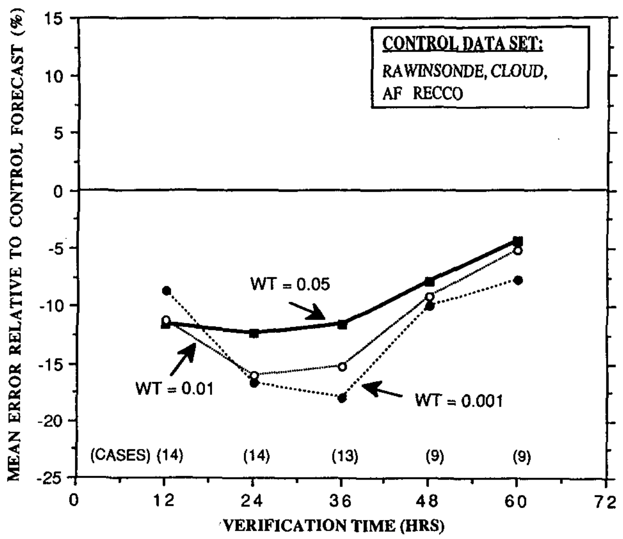

FIG. 5. Impact on mean VICBAR forecast errors of adding postprocessed ODW data to a control dataset, for various assignments of weight for the NMC background field. Errors are shown relative to the mean forecast error of the control, which was run using a background field weight of 0.05. The control dataset contains rawinsonde, reconnaissance, and cloud-motion data.

environment. In this section, several subsets of the postprocessed ODWs are taken and their impact is assessed against that of the complete dataset. The goals of this investigation are to determine optimal deployment strategies for future experiments and to study the sensitivity of the VICBAR model to different distributions of data. Forecasts for each of the 14 cases were run using the entire control dataset (rawinsondes, reconnaissance, and cloud motion data) plus the following *subsets* of the ODW data:

(i) ODWs in front semicircle,
(ii) ODWs in rear semicircle,
(iii) ODWs in left or right quadrants (cross-track quadrants),
(iv) ODWs in front or rear quadrants (along-track quadrants),
(v) alternate ODWs (starting with the second ODW),
(vi) alternate ODWs (starting with the first ODW),
(vii) ODWs within 625 km of storm center, and
(viii) ODWs outside 625 km from storm center.

The identification of ODWs within these regions was done in a storm-relative coordinate system. The terms *front, left,* etc., are relative to the (NHC best track) direction of storm motion; e.g., the left quadrant is centered 90° to the left of the direction of storm motion. There are no restrictions on distance from the storm for ODW subsets (i)–(vi) above.

Verifications for these ODW subsets are shown in Fig. 6. The front–back stratification (Fig. 6a) illustrates an expected result that information ahead of the storm is much more important than information behind the storm for the long-range forecasts. The differences between the front and back semicircle forecasts are significant at the 95% level at 48 and 60 h. For the 12-h verification, however, over two-thirds of the improvement comes from information behind the storm. By 24 h, the front and back contributions are about equal. An unexpected result is the additive nature of the contributions; that is, the reduction in MFE associated with the entire ODW dataset is very nearly equal to the sum of the separate improvements due to the front and back semicircle ODWs.

The dominant predictors in statistical–dynamical hurricane-forecast models tend to be located slightly ahead of the storm several hundred kilometers to the left and right of storm motion (Shapiro and Neumann 1984; Neumann 1988). This distribution of (height) predictors most dependably defines the large-scale environmental geopotential height gradient across the vortex. For VICBAR, however, a uniform environmental steering flow would be equally measurable from any orientation. The stratification shown in Fig. 6b divides the ODWs into the cross-track quadrants (left and right) and the along-track quadrants (front and back). Most of the ODW MFE reduction from 12 to 48 h is seen to be due to the cross-track ODWs.

Examination of the asymmetric wind fields (total wind − azimuthal mean vortex) for each of the 14 cases shows that the vortex steering flow tends to be determined by cyclonic and anticyclonic circulations centered several hundred kilometers to the left and right of the cyclone center relative to its direction of motion (e.g., Fig. 7; see also Lord 1989). The wind variation associated with these gyres is greater in the cross-track direction than in the along-track direction; therefore, the cross-track ODWs could be expected to provide more information about the structure of the environmental flow associated with the gyres. Numerous theoretical studies using barotropic models (e.g., Fiorino and Elsberry 1989) have documented the development of cyclonic and anticyclonic gyres in the environment of model hurricanes. Commonly known as *beta gyres,* these features develop in response to advection of environmental absolute vorticity by the symmetric vortex and tend to be structured similarly to the gyres shown in Fig. 7; however, it is difficult to determine how much of the structure shown in the figure is attributable to the beta gyres. Irrespective of the location of other, purely environmental vorticity centers, however, the beta gyres would be regularly centered in, and best sampled by, the cross-track quadrants.

Figure 6c shows the impact of two "half-density" ODW datasets obtained by removing every other ODW along each flight track. The two half-density sets are complementary (i.e., no ODW appears in both sets). The half-density datasets account for a substantial fraction of the total MFE reduction, and the figure appears to suggest that the number of deployed ODWs

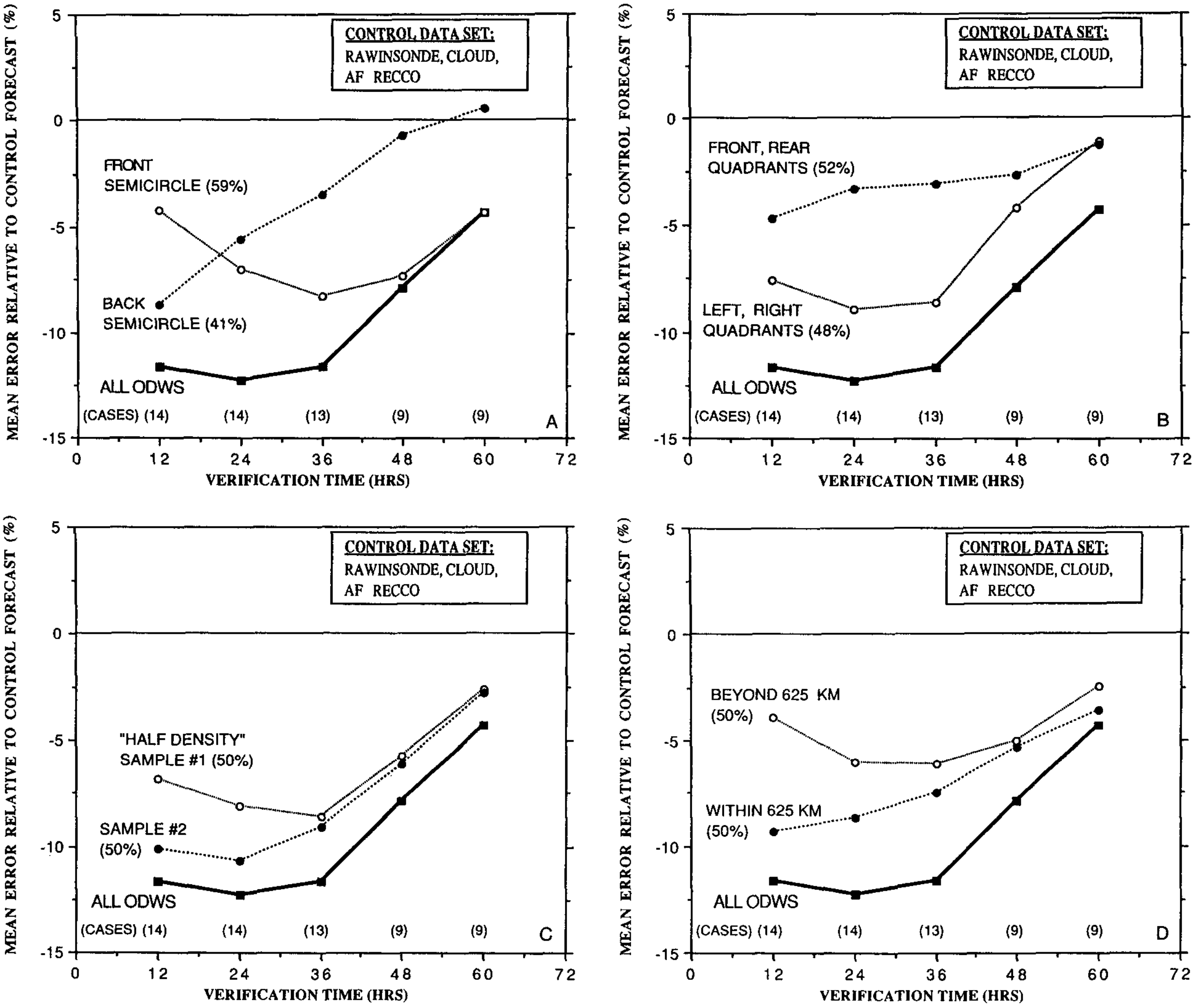

FIG. 6. Impact on mean VICBAR forecast errors of adding subsets of the postprocessed ODW data to a control dataset. The control dataset contains rawinsonde, air force reconnaissance, and cloud-motion data. Errors are shown relative to the mean forecast error of the control. Shown are the impacts of (a) front semicircle ODWs, rear semicircle ODWs; (b) ODWs in the left–right quadrants, ODWs in the front–rear quadrants; (c) two complementary "half-density" subsets of the ODW data, selected uniformly with respect to geography; and (d) ODWs inside 625 km of storm center, ODWs outside 625 km of storm center. In each panel, the heavy line indicates the impact of the complete ODW dataset.

could be reduced. However, some of the differences in MFE between the half and full sets are statistically significant (>99% at 36 h for both samples 1 and 2, and >95% at 12, 24, and 48 h for sample 1). The divergence of the two samples at the shorter-range verifications also suggests that a higher-density dataset, particularly near the storm, may be important. Reeder et al. (1991) have concluded that regular observations spaced 100–150 km apart are required to adequately define the environmental beta gyres. This is approximately the spacing of the full ODW dataset.

The effect of adding information close to rather than away from the center is shown in Fig. 6d. The dividing radius of 625 km separates the ODW dataset into roughly equal parts. Although none of the MFE differences between the two samples are significant at the 95% level, it is surprising that the ODWs close to the storm are more influential for both the short- and long-term forecasts. This may be an indication of the importance of a good initial motion diagnosis. There is also a hint that the two subsets in this radial stratification may be providing redundant environmental information; the combined MFE reductions from the two regions are greater than the MFE reduction from the full ODW dataset. This was not the case for the azimuthal stratifications (Fig. 6a,b).

6. Discussion and summary

The potential of ODW observations for reducing the errors of objective hurricane track forecasts can be

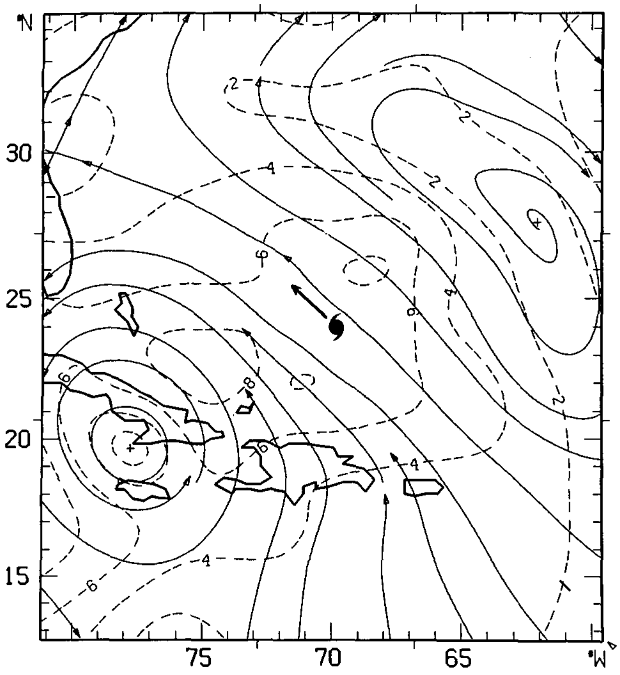

FIG. 7. Streamline–isotach analyses of the asymmetric deep-layer-mean (200–850 mb) wind for Gloria on 25 September 1985. The isotach contour interval is 2 m s^{-1}. Flow structure within 3° of the center is determined primarily by the imposed bogus vortex. Gloria's 12-h mean direction of motion is indicated by the plotted vector.

compared with the expense of obtaining the observations (Burpee et al. 1984). A typical synoptic-flow experiment involves about 55 ODWs (at $642 per ODW) and about 18 h of P-3 flight time (at $2500 per hour). Excluding overtime, per diem, and ferry time, the cost of the experiment is about $80 000. Hurricane warnings are typically issued 18–24 h prior to landfall for a length of coastline averaging 555 km; however, the area affected by hurricane conditions is generally less than 200 km. Thus, over 350 km of coastline is "overwarned" due to uncertainties in the forecast track. Sheets (1990) has estimated that preparation costs alone incurred by the public in coastal areas included in a hurricane warning are about $90 000 *per kilometer* of coastline warned. If the ODW observations lead to consistently improved objective track guidance when hurricanes threaten the United States coastline, and forecasters are able to reduce the overwarned area by only 5% (<20 km), the savings in warning response costs will easily exceed the cost of obtaining the observations.

The VICBAR track forecast model has performed well in comparison to the other objective guidance available to the hurricane forecasters (Aberson and DeMaria 1991) and is one of several models used by NHC in the preparation of their official hurricane track forecasts. ODW data collected during the synoptic-flow experiments resulted in highly consistent reductions in track forecast errors for the historical sample of 14 cases. At the critical verification times of 24–36 h (prior to landfall), when the decision to issue a hurricane warning is being made, the ODWs improved the model forecasts by 12%. Adjusting the analysis procedure to take greater advantage of the ODW observations resulted in 24–36-h improvements of 15%–16%. These reductions are comparable to the entire reduction in normalized 24-h NHC operational forecast errors obtained over the past 20–25 years (Sheets 1990). Flight-level data from the NOAA P-3 aircraft also produced some reductions in mean forecast error, but these were much smaller and less consistent than the ODW forecast-error reductions. These results suggest that the collection of ODW data in the hurricane environment can be a viable, cost-effective means of improving operational hurricane forecasts. They also support the conclusions of Neumann (1981, 1985) that a scarcity of observations in the hurricane environment, particularly in the midtroposphere, has been an important factor limiting the long-term improvement of hurricane track forecasts.

Forecasts made using azimuthally based subsets of the ODW data were suggestive of a quasi-linear relationship between the fraction of the environment sampled and the improvement of the VICBAR forecasts; i.e., the reduction in MFE due to all the ODWs was equal to the sum of the MFE reductions attributable to the ODWs from the various subsets. This may be due, in part, to the implementation of an objective analysis designed to maximize the impact of the ODWs. ODW subsets based on distance from the storm, however, appeared to provide some redundant information.

There was no evidence that the ODWs in this sample were of any more use in improving the bad VICBAR forecasts than they were in improving the good forecasts; that is, "busted" VICBAR control forecasts were not salvaged by adding the ODWs. However, the modest but consistent forecast improvements that were observed may be of more practical use to forecasters than successes that are occasionally dramatic but unpredictable. DeMaria et al. (1990) have suggested that observations on scales larger than those sampled here by the ODWs would have the largest impacts on track forecasts. The lack of "dramatic" changes to forecast track induced by the ODWs is consistent with this view. Since the ODWs were confined to within 1000 km of the storm center, it is natural to ask what additional reductions in MFE could be obtained through observations farther from the center. Longer-range aircraft would be required to adequately answer this question.

The impact of the ODW data in these barotropic forecasts was substantial. However, since ODWs are capable of determining the baroclinic structure of the hurricane environment as well, it is unlikely that the full potential of these observations has been realized in the VICBAR model. Work is beginning at HRD and elsewhere to study the impact of the ODW data on multilevel nested hurricane models.

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